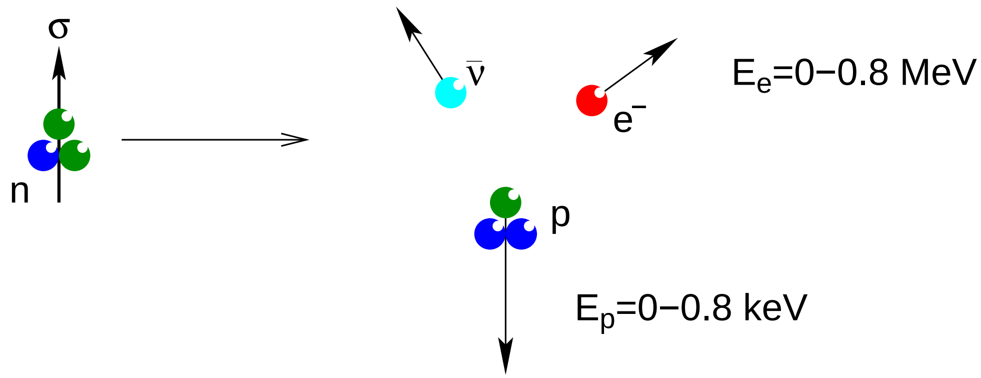
Neutron β-Decay



$$\rho(E_e) \approx \rho_s(E_e)\left\{1 + \beta a \cos\theta_{e\nu} + P_n\left[\beta A \cos\theta_{e\sigma} + B\cos\theta_{\nu\sigma}\right] + b\frac{m_e}{E_e}\right\}$$

$a \sim -0.1$ $\quad A \sim -0.1$ $\quad B \sim 1$ $\quad b \sim 0$

A and B require precision neutron polarimetry

Goals

- Determine $\lambda = G_A/G_V$ redundantly
  Measure both a and A (first precision measurement of a)
  Determine A from e^- and p asymmetries
  3σ deviation from value required for CKM unitarity

- Search for Fierz interference term b
  Sensitive to scalar and tensor couplings
  Non-zero value suggested by π^+ β-decay results
  Never measured

- Measure B precisely
  Sensitive to deviations from $V - A$ theory
  e.g. Mass of right-hand boson

Measuring V_{ud} with Neutron Decay

$$V_{ud}^2 = \frac{K/\ln 2}{G_F^2\left(1+\Delta_R^V\right)(1+3\lambda^2)f(1+\delta_R)\tau_n}, \qquad \lambda = G'_A/G'_V \approx -1.265$$

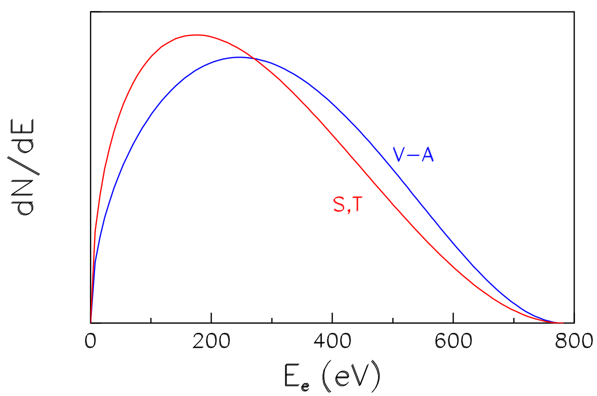
$$\begin{aligned} 1 - V^2 &= 0.0047 \pm 0.0051 \\ &= 0.0047 \pm \underset{\lambda}{0.0049} \pm \underset{\tau_n}{0.0010} \pm \underset{V_{us}}{0.0010} \pm \underset{\mathrm{RC}}{0.0007} \end{aligned}$$

$$\frac{d\lambda}{da} = 3.3 \qquad \frac{d\lambda}{dA} = 2.6 \qquad \frac{d\lambda}{dB} = 13.4$$

$$\Delta a = 2.3 \times 10^{-4} \qquad \Delta A = 3.0 \times 10^{-4} \qquad \Delta B = 0.6 \times 10^{-4}$$

$$\longrightarrow \Delta V_{\lambda}^2 = 0.0010$$

Measurement of b Coefficient



- Important physics measurement

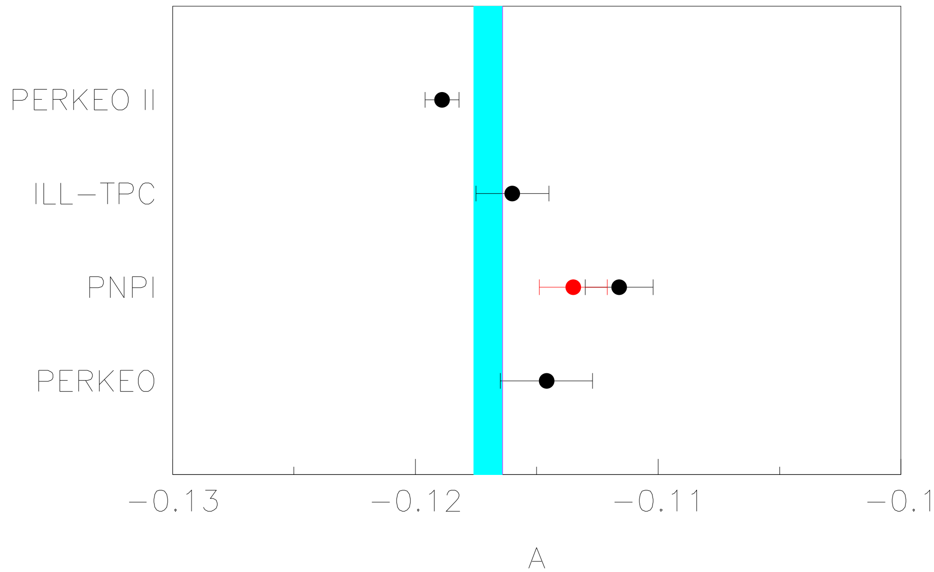
  $b = 0$ in standard model

  $b \neq 0$ for scalar or tensor couplings

  Never determined from neutron β-decay

  Results of π^+ β-decay suggest $b \neq 0$
- $\Delta b = 0.001$ (statistics)
- Needed to extract V_{ud} from λ, τ_n

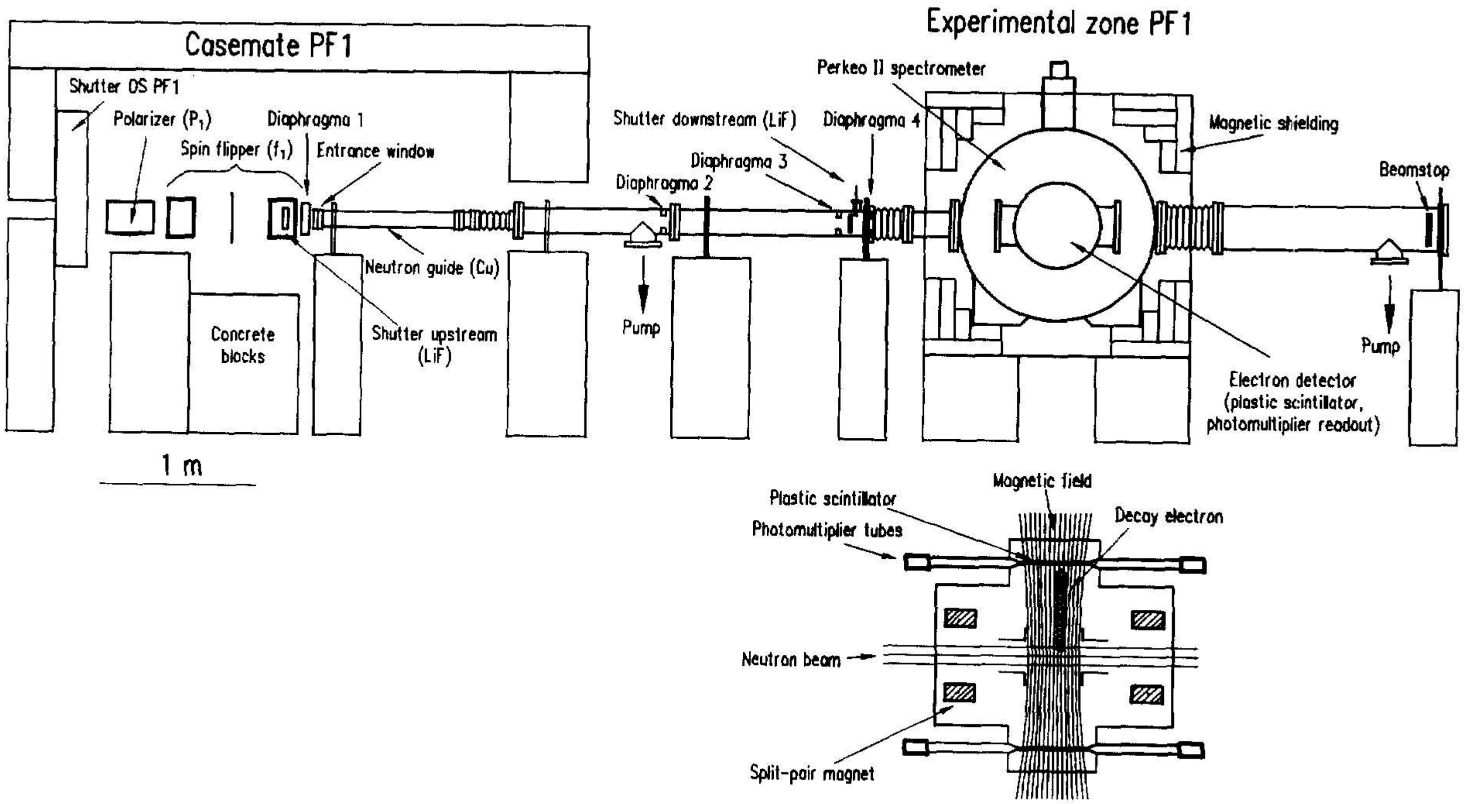
Consistency of Existing Measurements of A



$$A = -0.1170 \pm 0.0006\ (0.0015) \quad \chi^2 = 24.2 \quad P = 8 \times 10^{-5}$$

$$A = -0.1173 \pm 0.0006\ (0.0012) \quad \chi^2 = 15.3 \quad P = 4 \times 10^{-3}$$

PERKEO II



H. Abele, *et al.* Physics Letters B **407**, 212 (1997).

Sources of Systematic Error in Previous Experiments

1. Neutron polarization determined in auxiliary experiments
2. Detector properties
   Resolution, efficiency, stability, homogeneity
3. Background subtraction: singles measurements needed
4. Fiducial volume defined by material apertures
   Energy loss, scattering
5. Magnetic field pinch reverses particle trajectories
6. Electron back-scattering from detectors

New Techniques to Address Systematic Errors

1. *In situ*, absolute neutron polarization established

2. Large-area segmented silicon detectors

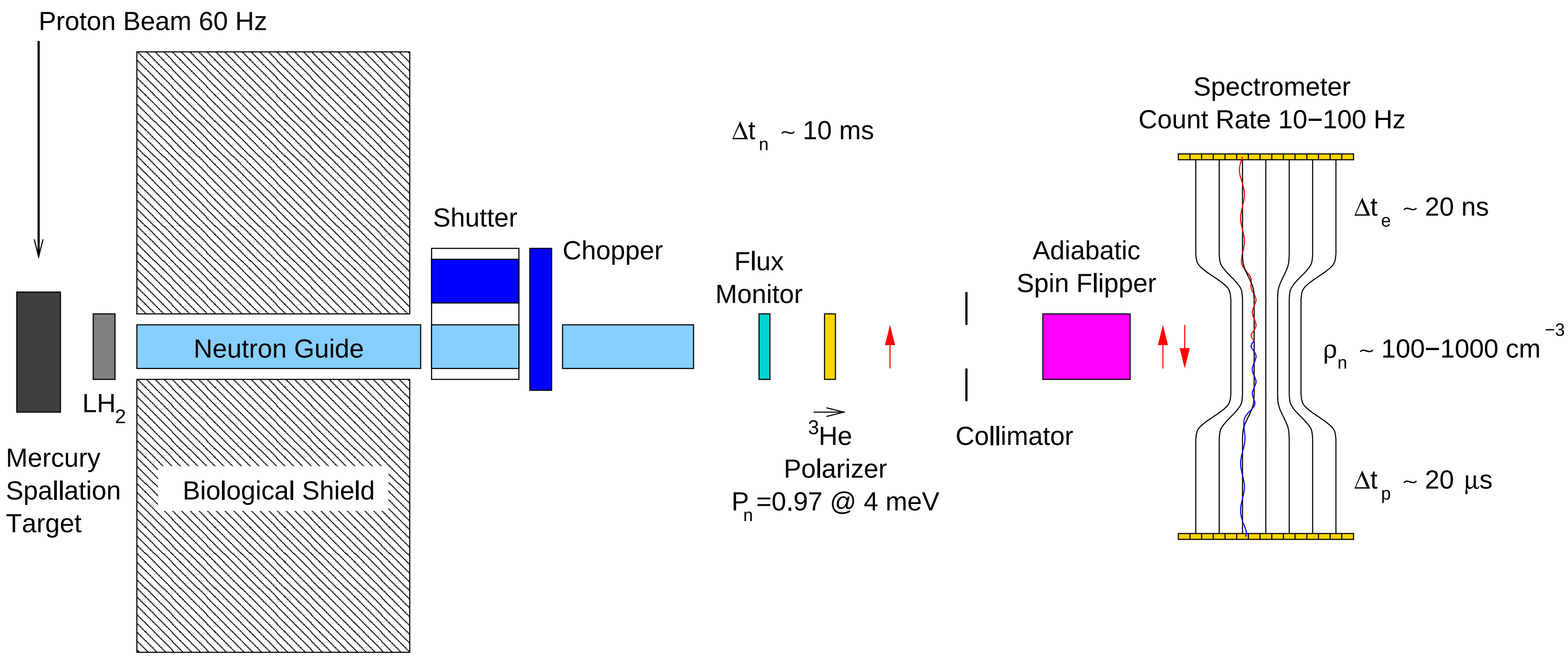
3. Detect e and p in coincidence

4. Segmented detectors image decay volume

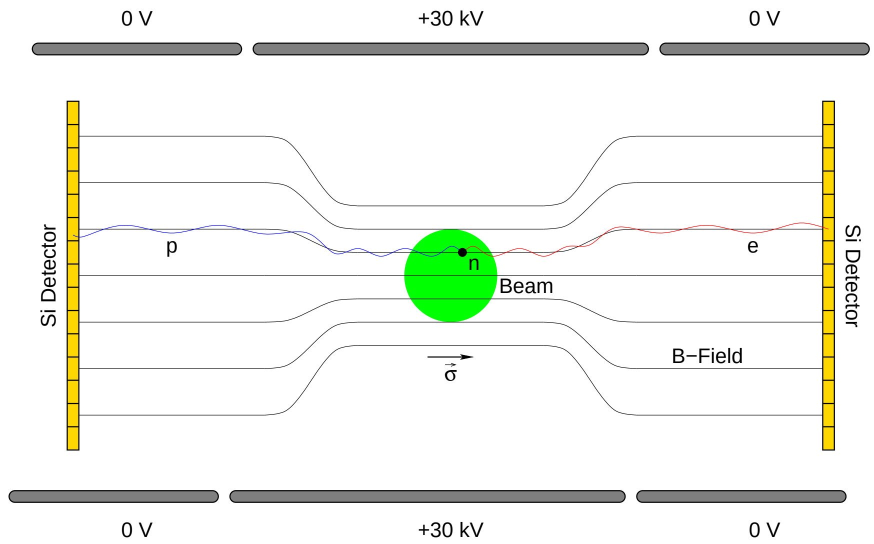
5. All decays in homogeneous B region
   No material apertures or grids

6. Transient digitize events for reconstruction of backscattering events

Neutron β-Decay with Cold Neutrons at SNS



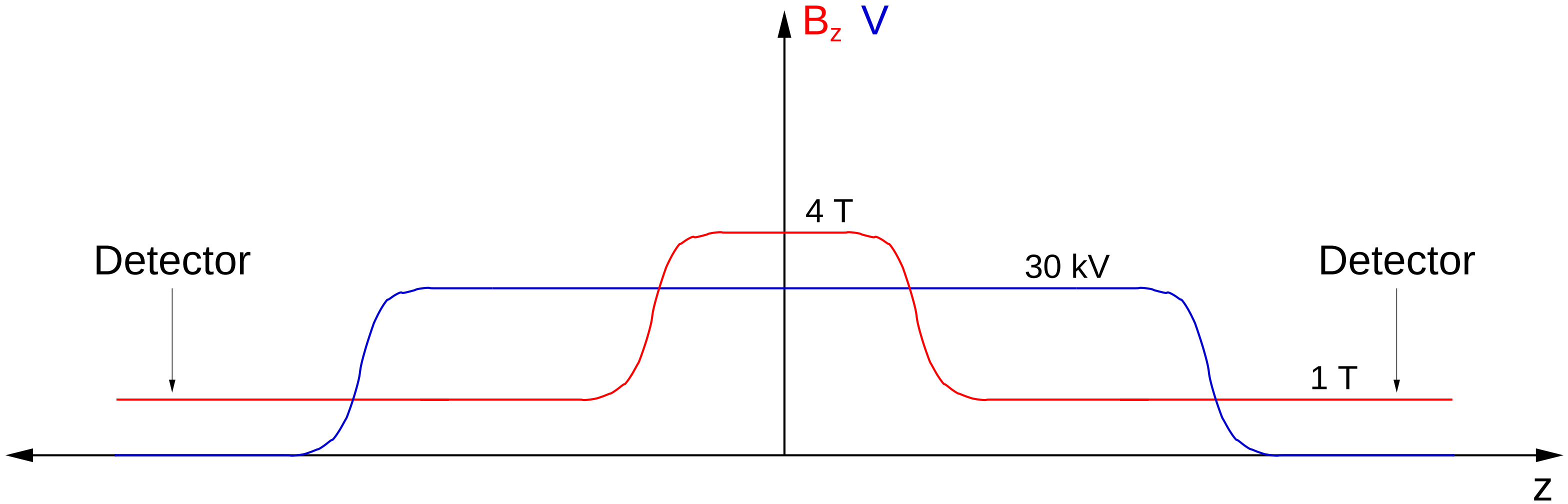
Neutron β-Decay Spectrometer



- Two 2π detectors
- e backscattering monitored
- $\Delta t \sim 1$ ns
- $\Delta E \leq 5$ keV

- $e - p$ coincidence
- Beam imaged by detectors
- *In situ* background measurement
- No material apertures

Magnetic and Electric Fields



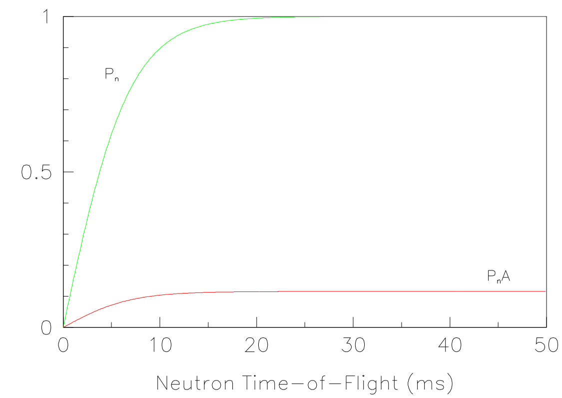
- Magnetic field expansion: $\vec{p}_e$ more normal to detector
- Magnetic field gradient reflects backscattered electrons
- Electric field accelerates protons

In Situ **Polarization Measurement**

- Neutrons polarized by transmission through polarized ^{3}He
- Measure asymmetries as a function of TOF
- Exact relation between neutron polarization and TOF
- *In situ* determination of P_n to $< 0.1\%$

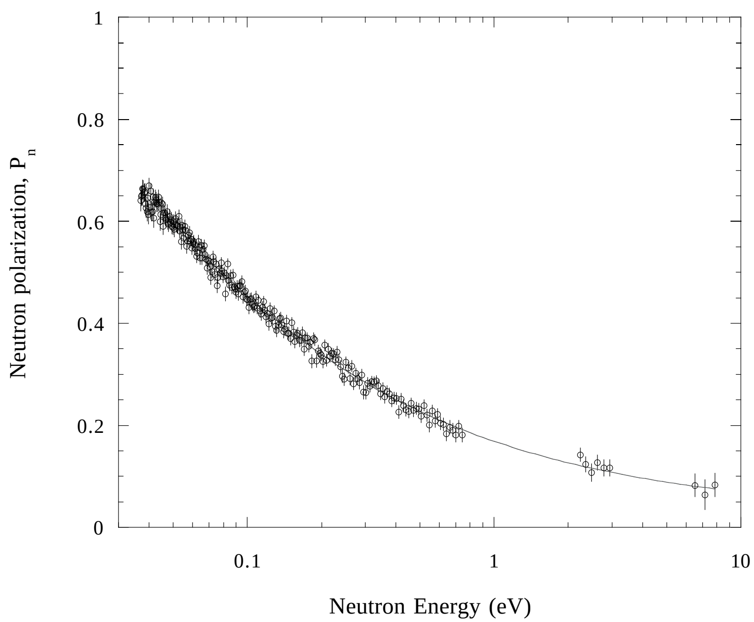
$$P_n = \tanh(-t/\tau)$$

$$AP_n = A\tanh(-t/\tau)$$



Extract A and B from two-parameter fits to decay data

Absolute Neutron Polarimetry at LANSCE



$\Delta P_n \leq 0.3\%$

S.I. Penttilä, *et al.*

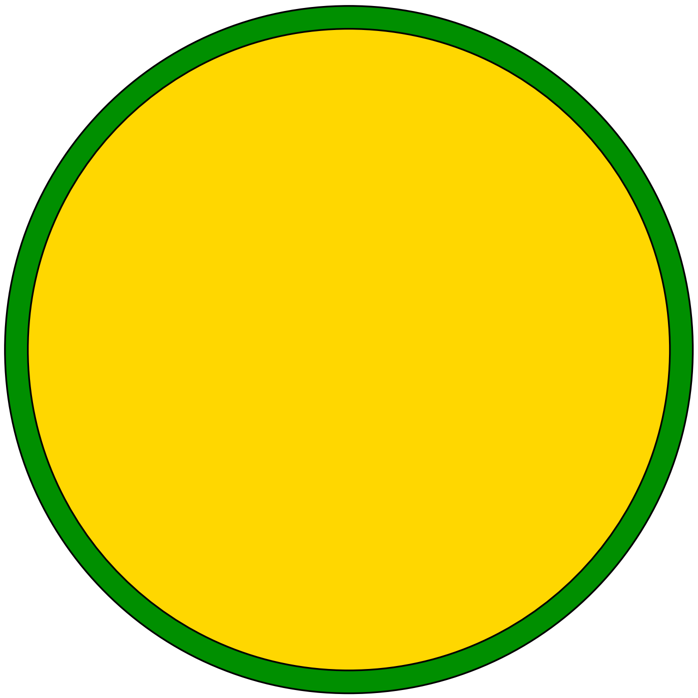
Constructed for $\vec{n} + p \rightarrow d + \gamma$

Straight forward extension of polarimetry method to $\sim 10^{-4}$

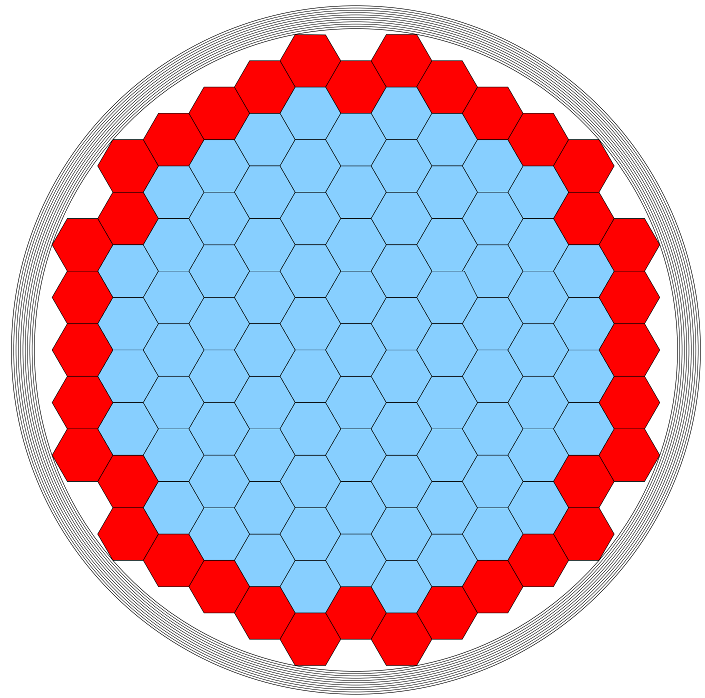
Advantages of Silicon Detectors

- Thin dead layer: $\Delta E_e \leq 5$ eV, $\Delta E_p \leq 5$ keV measured
- Almost unity efficiency: small well-understood corrections
- Extremely uniform dead layer: no wires, foils, supports, etc.
- 4π detection of electrons and protons: coincidence
- Imaging: defines fiducial volume without material apertures, provides *in situ* background measurement

Preliminary Detector Design



Junction Side
(Particles Incident)



Ohmic Side
(Readout)

15 cm Diameter, 2 mm Thick, 127 Channel

Anticipated Statistical Uncertainty at SNS

Parameter	Rate (Hz)	Uncertainty	PDG Uncertainty
b	800	1.1×10^{-4}	—
a	800	1.4×10^{-4}	50×10^{-4}
A	160	0.9×10^{-4}	13×10^{-4}
B	160	1.5×10^{-4}	40×10^{-4}

Assume two runs of 1×10^{7} s (polarized, unpolarized)

Anticipated Statistical Uncertainty at LANSCE

Parameter	Rate (Hz)	Uncertainty	PDG Uncertainty
b	40	5×10^{-4}	—
a	40	6×10^{-4}	50×10^{-4}

Assume two runs of 5×10^{6} s

Systematic Errors Analyzed

- Electron backscattering
- Proton backscattering
- Neutron depolarization effects
  - Depolarization in glass window
  - Finite neutron pulse width
  - $1/v$ n-^{3}He cross section dependence
- Magnetic field inhomogeneities
- Proton arrival time

All systematics $\sim 10^{-4}$

Status

- ^{3}He polarizer exists
  In situ polarimetry technique demonstrated
- Detector technology proven
  Deadlayer measured
  Timing resolution measured
  10 cm diameter, 2 mm thick detector under development
- Preliminary spectrometer design
  Magnet design and cost study complete
  HV electrode structure designed by UTenn/ORNL
- ADC/DSP design and cost study in progress
  100 MHz 12 bit prototype tested by ORNL
- LANSCE FP12 under construction
  Neutron guide in place
  Shielding being installed
  Flux measured

Preliminary Cost Estimate

		Cost	
WBS	Task	a,b	A,B
1	Beam Line Modifications	\$160k	\$160k
2	Spectrometer	\$1658k	
3	Detectors	\$170k	
4	Detector Electronics	\$717k	
5	Polarizer		\$111k
6	Spin Flipper		\$45k
7	Beam Monitors	\$15k	
8	Transverse Field		\$192k

Total Capital \$3.2M (DOE, NSF, and Institutional)

Includes contingency and overhead

Proposed Schedule

Milestone	Date
Final Proposal	Jun 2003
Begin Construction	Jan 2005
Commissioning (LANSCE)	Jan 2007
Commissioning (SNS)	Jan 2009

- Physics Results before SNS

- Tested apparatus when SNS turns on

Detector Requirements

- Detect electrons $E_e \leq 800$ keV
  2 mm thick

- Detect protons $E_p \sim 30$ keV
  Entrance window ~ 100 nm

- Determine electron energy
  $\Delta E \sim$ few keV

- Resolve electron timing
  $\Delta t \sim 1$ ns
  Cooled detector and FET, ~ 1 kV/mm bias

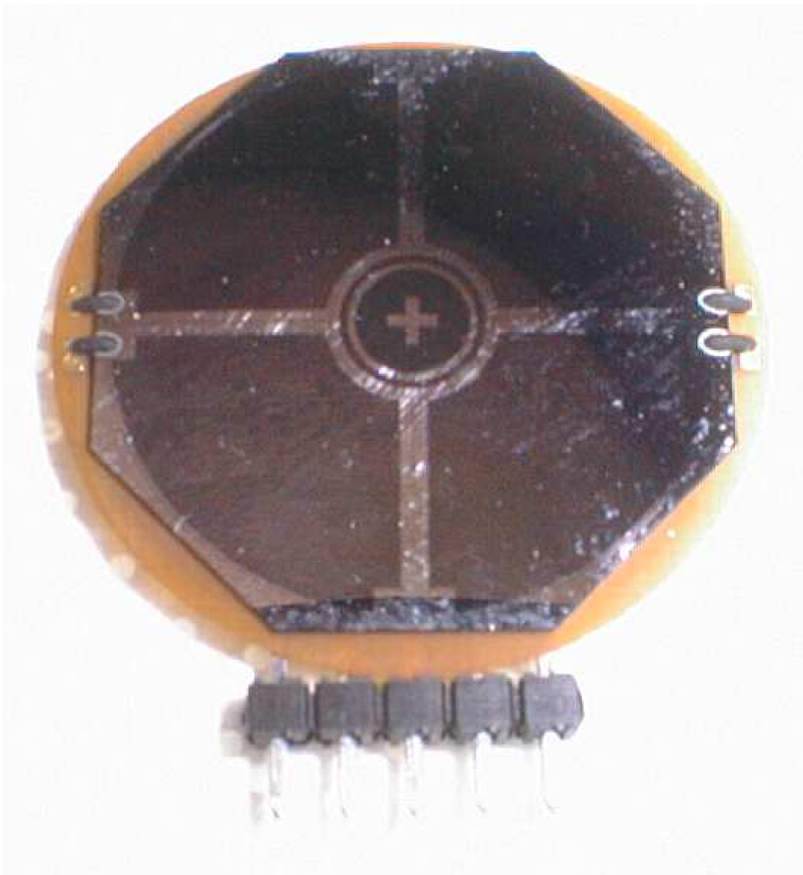
- High efficiency, hermetic
  15 cm wafer

Test Detectors

- Ion implanted detectors: few cm^2, 300 μm thick
  Entrance window studies

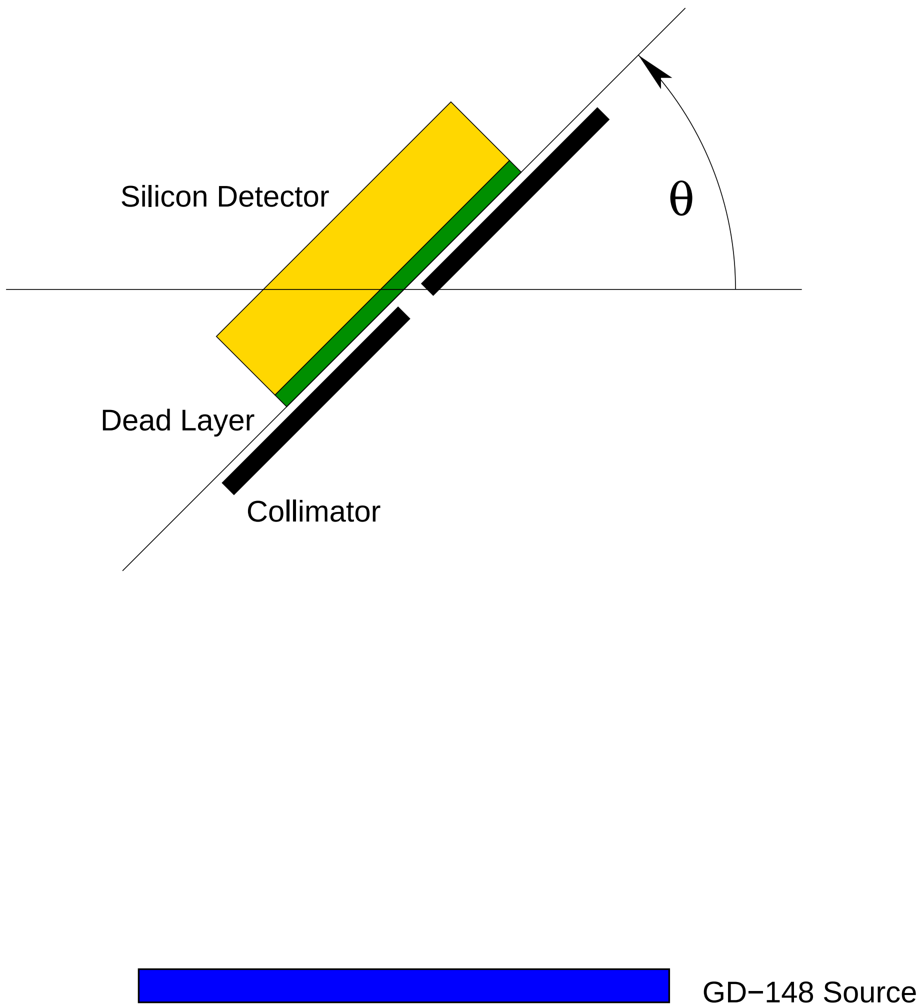
- Surface barrier detectors: 1 cm^2, 2 mm thick
  Timing studies

Prototype Detector

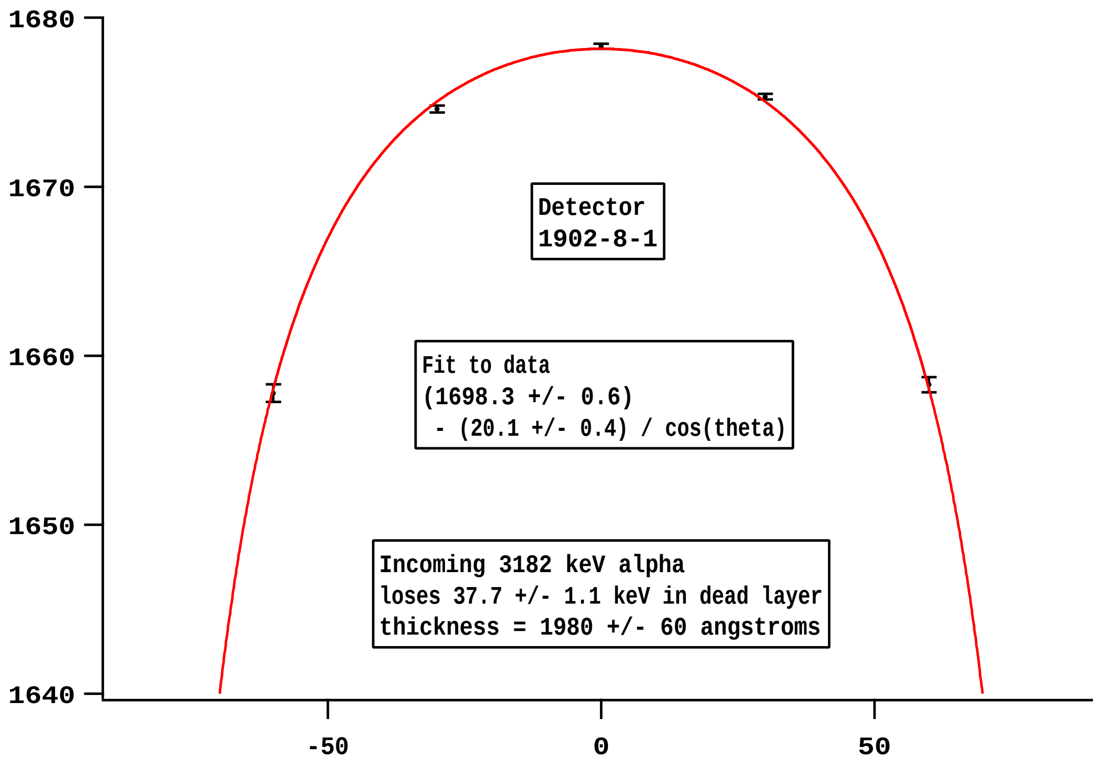


56 nm dead layer ($< 20\ \mu g/cm^2$)

Dead Layer Measurements



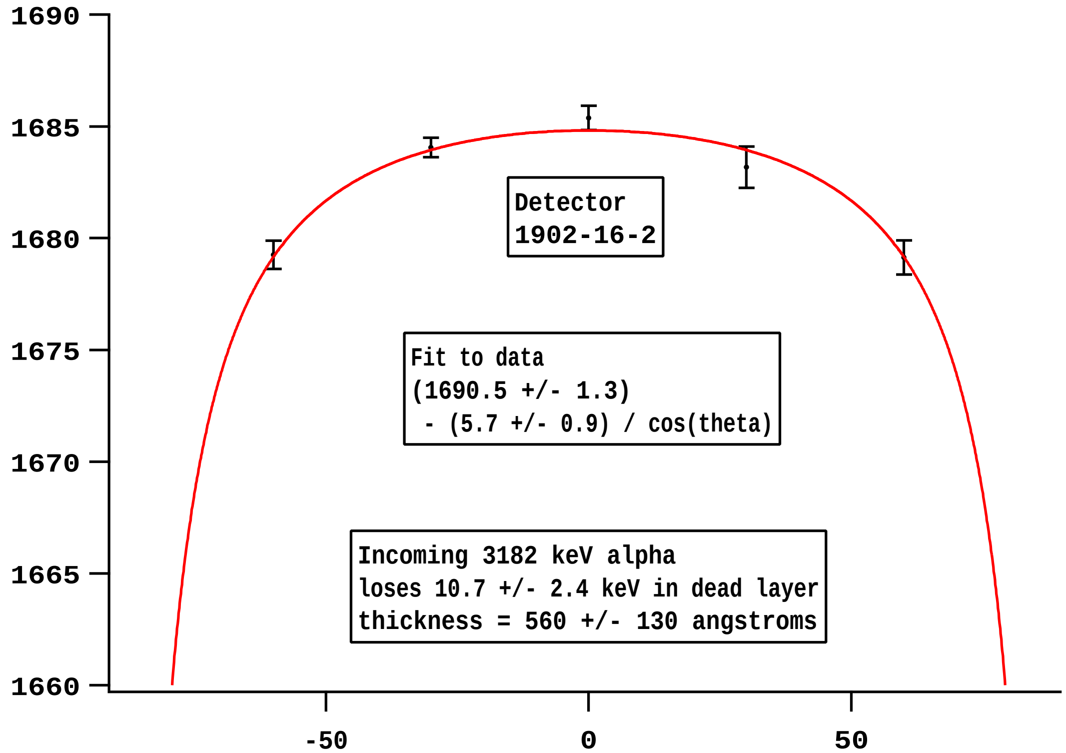
Normal Silicon Detector



200 nm Dead Layer

$E_{\text{loss}} = 14$ keV for $E_p = 30$ keV

Thin Dead Layer Silicon Detector



56 nm Dead Layer

$E_{\text{loss}} = 5$ keV for $E_p = 30$ keV

Detector Properties Checklist

- 2 mm thick
  2 mm thick wafers in 10 cm diameter
  15 cm diameter?

- <100 nm entrance window
  <100 nm measured
  Metal?

- $\Delta E \sim$ few keV
  OK

- $\Delta t \sim 1$ ns
  OK

- 1 kV/mm bias
  1 kV (total) bias available 2 kV?